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Digital Twin Technology in Operations and Maintenance Management in the Construction Industry

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Abstract

As an important pillar industry supporting the development of the national economy, the importance of operation and maintenance (O&M) management is self-evident, and digital twin technology brings new opportunities and challenges for O&M management to become intensive and intelligent. The use of digital twin technology, breaking the traditional operation and maintenance methods, through real-time collection and analysis of data from physical entities (equipment, systems or processes), can effectively improve productivity and reduce costs. In this paper, for the application of digital twin technology in O&M management in the construction industry, the development history of digital twin technology is reviewed, and the gradual evolution of the digital twin concept from its inception to maturity is sorted out; four aspects of equipment condition monitoring and predictive maintenance, fault diagnosis and intelligent warning, human-machine collaboration and training simulation, and energy optimization and energy management are analyzed; and the difficulties in the application are discussed and outlook, and obtain conclusions.

Keywords

Digital Twin; Operations and Maintenance Management; Digitization; Cost Reduction and Efficiency.

1. Introduction

With the advancement of technology and society,intelligent construction driven by digital technology innovation is becoming a new trend in the construction industry[1].Consequently, establishing a digitalized management system for operations and maintenance (O&M) poses a challenge for the future development of the construction sector[2].Through digitalization,real-time monitoring and management of the building's interior can be achieved,enabling timely access to equipment's operational status and health conditions. This not only enhances management efficiency but also effectively addresses emergencies and disasters,ensuring the safety of users' lives and properties,and promoting sustainable development in the construction industry. Therefore,establishing a robust digitalized O&M management system is not only a future trend in building development but also an important approach to overcome the limitations of traditional O&M management in the face of rapid technological advancements.

The O&M phase,being the longest and most critical stage in the lifecycle of a building where the return on investment is realized,has unquestionable importance in the digital era. With the continuous promotion of Industry 4.0 and Digital China,the wave of industrialization and digitization has swept across the globe. According to the PwC Strategy& report "Global Digital Operations Study 2018",by

2030,digitalization and intelligent automation are expected to contribute 14% of global GDP growth,equivalent to a value of $15 trillion USD. This highlights the vast market potential for industrial digitization. Against the backdrop of digital transformation,building digital twins have emerged as a new technology in recent years. It combines the physical building with its digital model,enabling real-time monitoring of building operations,predictive maintenance,fault diagnosis,and optimization recommendations[3]. For the construction industry already immersed in the digital revolution,the application of digital twin technology in O&M management is particularly significant.

2. Research Method

2.1 Development History of Digital Twin Technology

The prototype of digital twins first appeared in the late 1960s and early 1970s[4]. During this period,researchers completed the design of Apollo 13,aiming to provide a backup and verification mechanism for NASA's space exploration[5]. It can be observed that the core idea of this process is similar to that of digital twins. The concept of a digital twin model was initially proposed by Professor Grieves from the Florida Institute of Technology in 2002[6]. At that time,the technology was referred to as the "Conceptual Ideal for PLM" rather than "digital twin",but its main components were almost identical to those of digital twins: physical entities,virtual models,measurement data from physical entities to virtual models,information and processes from virtual models to physical entities. When describing this concept,he defined it as a digital representation of physical entities in the real world,capable of reflecting the structure,status,and behavior of physical entities,as well as their related environment,processes,and effects,for monitoring,simulation,and prediction of the operation status and behavior of physical systems. The goal of this concept is to reflect and analyze the state of the physical world in real-time through a digital model to support decision-making and optimization in the physical world. Subsequently,the concept of digital twins gradually developed and was referred to as the "Mirrored Spaces Model" in 2005[6] and the "Information Mirroring Model" in 2006[7]. Throughout the development process of digital twins,although its name underwent several changes,there were minimal differences in the composition and core ideas of digital twins[8].

NASA and the United States Air Force (USAF) then proposed the concept of "digital twins" in 2012. Their defined concept was centered around "simulation" and aimed to reflect the entire lifecycle of components. Although the core idea of digital twins had been around for many years,it wasn't until 2017 that the topic gained attention in the academic community. The final key development milestone was the contribution of Professor Tao[9] from Beihang University. Based on Michael Grieves' white paper[10],the concept model of digital twins consists of three parts: physical products in the real space,simulated products in the virtual space,and the interrelationships between the two. Building on this,in 2016,Professor Tao[9] proposed the five-dimensional architecture of digital twins. To illustrate the development of the digital twin model clearly,Fig.1 provides a timeline of the development process of digital twins from the 1960s to the present.

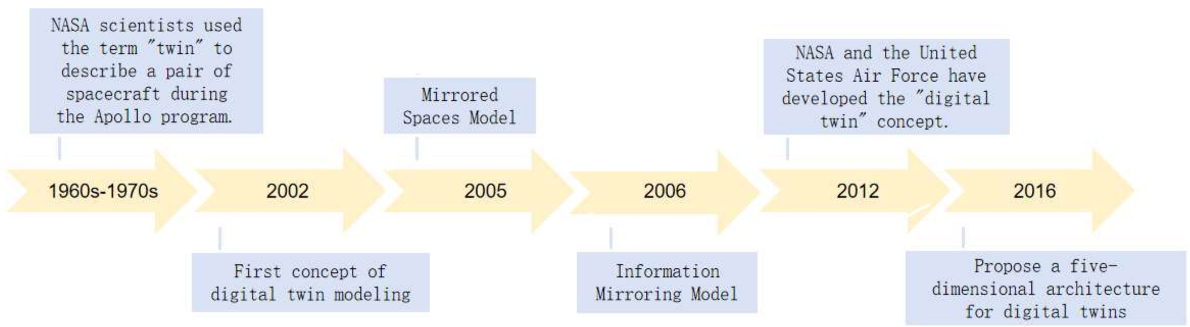

Fig.1 Timeline of the digital twin development process

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2.2 Literature Data Analysis

This paper adopts a systematic literature review approach. Two databases,namely China National Knowledge Infrastructure (CNKI) and Web of Science,were selected to retrieve relevant literature. The search was conducted using the keywords "Operations Management" AND "Digital Twin" for CNKI and "Operations Management" AND "Digital Twin" for Web of Science. The search was conducted up until December 2023. The results yielded a total of 417 and 626 literature entries in the CNKI and Web of Science databases,respectively,as shown in Fig.2. It can be observed from the data in the table that research combining operations management with digital twin technology has been on the rise since 2017,with a steady increase in the number of publications. Furthermore,both domestic and international research on related theories and applications have shown a rapid development trend,particularly after 2020. Based on the literature search results,this paper provides a retrospective and prospective analysis of the application of digital twin technology in the operations management phase.

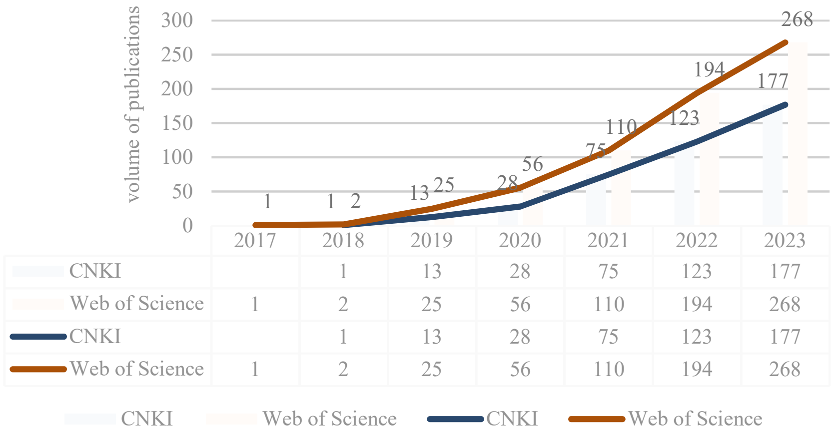

Fig.2 Number of articles related to digital twin in O&M process

3. Application Research of Digital Twins in Operations Management

Over the past few decades, energy efficiency has increasingly gained attention in the fields of architecture, engineering, construction, and operations and maintenance (O&M). Digital twinning has proven to be an effective tool in advancing O&M across various stages[11]. Through literature analysis, it is evident that digital twinning technology holds significant potential for applications in maintenance management. Its specialized applications, as illustrated in Fig.5, encompass equipment condition monitoring and predictive maintenance, fault diagnosis and intelligent warning systems, human-machine collaboration and training simulations, as well as energy optimization and management. These applications offer substantial benefits in enhancing efficiency, reliability, and sustainability.

3.1 Equipment Condition Monitoring and Predictive Maintenance

Traditional methods rely on analyzing historical data and experience to model the degradation process of equipment as a reference for prediction[12]. The emergence of digital twin technology has provided new directions for equipment condition monitoring and predictive maintenance,and researchers have made contributions from different perspectives. BOOYSE et al. [13] proposed a deep digital twin architecture for deep learning-based equipment prediction and health monitoring framework,aiming to overcome the over-reliance on past failure data. TONG et al.[14]introduced a real-time machining data application and service based on intelligent machine tool digital twins,which enables real-time monitoring of equipment status and timely processing of collected data. This predictive maintenance approach helps operators adjust equipment maintenance plans

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promptly,reduce downtime caused by unexpected equipment failures,and improve equipment reliability and operational efficiency.

3.2 Fault Diagnosis and Intelligent Early Warning

Digital twinning technology enables the identification of potential equipment failures by combining data analysis and machine learning algorithms, thus facilitating intelligent diagnosis and early warning of equipment malfunctions. Li Conglin et al.[15]applied the theory of digital twinning in conjunction with human behavior modeling to construct scenarios of abnormal passenger behavior in elevators, augmenting the twinning data related to such behaviors. Similarly, Luo Wenliang et al.[16]addressed the challenges in fault diagnosis and prediction within a dynamic coupled kiln system and proposed a fusion-driven approach that integrates digital twinning with neural networks for fault diagnosis and early warning in the kiln system.D.J. Wagg et al.[17] developed a digital twinning model for wind power generation, as depicted in Fig.3. The model collects data from the physical twin and subsequently sends control and scheduling instructions as required for monitoring and operation. The collected data, which could be real-time, comparable, or traditional data, is combined with numerical models and physical test beds. These test beds may include additional online equipment, systems, or databases to provide necessary modeling capabilities. By further providing users with visual representations and quantitative feedback, the coordination among these different components is facilitated. The warning signals generated by the digital twinning model can alert maintenance personnel to take timely measures, thereby avoiding production losses and mitigating safety risks associated with equipment failures.

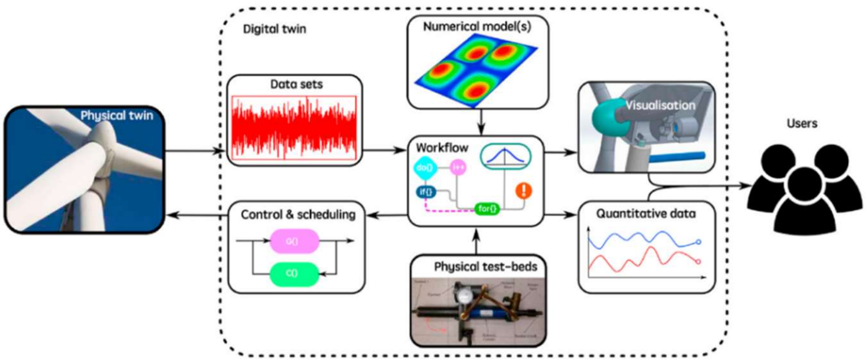

Fig.3 Example DT for a wind farm based on[17]

3.3 Human-Machine Collaboration and Training Simulation

Digital twin technology can provide operators with realistic virtual environments and training simulation platforms. In these virtual environments,operators can engage in real-time practice and emergency drills for equipment operations,thereby improving their ability and efficiency in responding to unexpected situations. Furthermore,digital twin models can interact with operators in real-time,providing operational guidance and technical support,helping them better understand the operational principles and workflows of the equipment. Siemens,a leading provider of wind power and renewable energy solutions,utilizes digital twin technology to create virtual models of wind turbines for training operators. The digital twin model simulates various components and operational scenarios of the wind turbine,allowing operators to perform maintenance and troubleshooting exercises in a virtual environment. Similarly,Schlumberger,a global leader in oilfield services,utilizes digital twin models to simulate processes such as oil well drilling,reservoir development,and oilfield production,enabling trainees to practice actual operations and emergency handling in a virtual environment.Digital twin technology is utilized to provide highly realistic virtual training environments for O&M personnel to improve their skill levels and coping abilities. These cases demonstrate the practical application and potential of digital twin technology in O&M training.

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Examples of well-known companies and their software are listed in[18], as shown in fig.4.All of which have invested heavily in research and development in the field of digital twins, significantly contributing to the promotion and development of the technology. At the same time, the use of digital twins has brought practical benefits to customers.

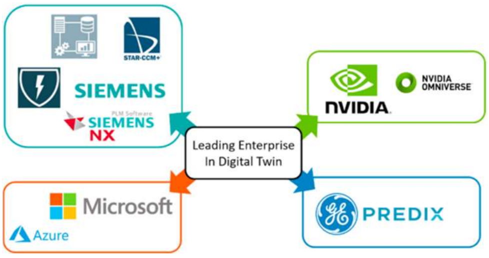

Fig. 4 Leading enterprise in digital twin and its software[18].

3.4 Energy Optimization and Energy Management

Through digital twinning technology, virtual models can be created to accurately represent the energy consumption of equipment and systems. These models are based on factors such as equipment specifications, workload, operating parameters, and are continuously updated with real-time data. By analyzing the models, the main sources of energy consumption, energy-intensive processes, and potential optimization opportunities can be identified[19]. With digital twinning models, virtual experiments and simulations can be conducted to predict future energy demands. The models can simulate different scenarios and conditions to determine the impact of various factors on energy requirements. This aids in predicting future energy consumption trends and providing corresponding forecasting results[18]. Lin Feng et al.[20] proposed a digital twinning system design for an energy internet based on the concept of "dual carbon," which includes the physical perception layer, transmission and interaction layer, data sharing layer, application service layer, and security protection. By setting carbon dioxide emissions and investment cost objectives and employing harmony search algorithms, energy internet planning and system design are realized. Through digital twinning technology, O&M managers can gain a better understanding of energy consumption patterns and trends. They can devise effective optimization measures, monitor and adjust energy usage in real-time, and work towards sustainable development and environmental protection goals.

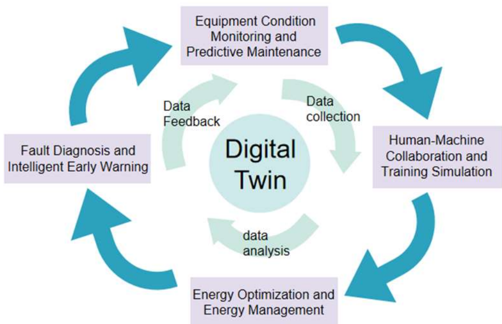

Fig.5 Performance of digital twin application in O&M management

4. Discussion and Outlook

Utilizing digital twin technology to obtain real-time data from buildings provides data-driven decision support for operations and maintenance teams. This enables the optimization of building performance and maximization of energy efficiency,thereby achieving energy-saving goals. Additionally,digital twin technology enables predictive maintenance of building equipment, making maintenance work more efficient. These measures greatly enhance the management level and work efficiency of operations and maintenance[21].

However,as digital twin technology permeates operations and maintenance management, it also brings about information explosion,making it challenging to manage the massive amount of data using traditional methods. Without proper management,this abundance of data can become data junk and pose a significant security threat. Therefore,foundational research on information security,collaborative models,management methods,and implementation standards is a prerequisite for engineering applications.

During the operational phase,digital twin technology may face some challenges and difficulties, including:

Data Quality: Digital twin technology relies on a large volume of real-time data to establish accurate models and perform effective predictions. However,the quality,completeness,and timeliness of the data can be compromised,leading to decreased accuracy of the digital twin model[22].

Model Precision and Accuracy: The accuracy of digital twin models depends on their precise representation of the actual system. However,the complexity and dynamics of the real world can lead to a decrease in model precision,especially when dealing with uncertainty and unexpected events[23].

This article provides a retrospective analysis of the application of digital twin technology in operations and maintenance(O&M) management. It begins by reviewing the significant milestones in the development of digital twin technology,highlighting its progressive and rapid advancement. The analysis is then divided into three parts: equipment condition monitoring and predictive maintenance,fault diagnosis and intelligent warning,and human-machine collaboration and training simulation. A total of 1,043 papers were retrieved from two databases,with a concentrated publication trend in recent years. This indicates that researchers recognize the development potential of digital twin technology in O&M management and underscores its status as an emerging field that urgently requires further research and exploration.

Looking ahead, there is a need to strengthen the integration of virtual and physical interactions in the application of digital twin technology in O&M management, thereby providing O&M personnel with a more realistic and convenient working environment. With the advancement of technology, future digital twin technology can integrate with artificial intelligence and machine learning systems, enabling models to autonomously learn and provide intelligent assistance. This means that digital twin models can continuously optimize themselves based on real-time data and provide O&M personnel with more intelligent recommendations and support, helping them manage and maintain equipment more effectively.

References

[1] Liu, G., Ma, Z., Zeng, B., et al. (2023). A review of the application of digital twin technology in construction engineering. Journal of Civil, Architectural & Environmental Engineering, 15(06), 1-8. DOI: 10.16670/j.cnki.cn11-5823/tu.2023.06.01.

[2] Lin, K., Zheng, J., & Lu, X. (2024). Application of digital twin technology in civil engineering: A review and outlook. Journal of Harbin Institute of Technology, 56(01), 1-16.

[3] Li, D. (2022, June 10). Broad prospects for the application of digital twin. Economic Daily. Retrieved from http://paper.ce.cn/pc/comtent/202206/10/content_255383.html.

[4] Aydemir, H., Zengin, U., & Durak, U. (2020). The Digital Twin Paradigm for Aircraft Review and Outlook. In AIAA Scitech 2020 Forum. http://doi.org/10.2514/6.2020-0553.

[5] Barricelli, B. R., Casiraghi, E., & Fogli, D. (2019). A Survey on Digital Twin: Definitions, Characteristics, Applications, and Design Implications. IEEE Access, 7, 167653–167671.

[6] Grieves, M. W. (2005). Product lifecycle management: The new paradigm for enterprises. International Journal of Product Development, 2(1/2), 71. DOI: 10.1504/IJPD.2005.006669.

[7] Grieves, M. W. (2006). Product Lifecycle Management: Driving the Next Generation of Lean Thinking.Retrieved from https://onlinelibrary.wiley.com/doi/full/10.1111/j.1540-5885.2007.00250_2.x.

[8] Su, S., Zhong, R. Y., & Jiang, Y. (2023). Digital twin and its potential applications in the construction industry: State-of-the-art review and a conceptual framework. Advanced Engineering Informatics, 57, 102030. DOI: 10.1016/j.aei.2023.102030.

[9] Tao, F., Zhang, M., Liu, Y., & Nee, A. Y. C. (2018). Digital twin-driven prognostics and health management for complex equipment. CIRP Annals - Manufacturing Technology, 67(1), 169-172.

[10] Grieves, M. (2015). Digital Twin: Manufacturing Excellence through Virtual Factory Replication.

[11] Bortolini,R;Rodrigues,R.;Alavi,H.;Vecchia,L.F.D.;Forcada,N.Digital Twins'Applications for Building Energy Efficiency:A Review.Energies 2022,15,7002.

[12] Mi, S., Feng, Y., Zheng, H., et al. (Year). Prediction maintenance integrated decision-making approach supported by digital twin-driven cooperative awareness and interconnection framework.

[13] Booysen, W., Wilke, D., & Heyns, S. (2019). Deep digital twins for detection, diagnostics, and prognostics. Mechanical Systems and Signal Processing, 140, 1-25.

[14] Tong, X., Liu, Q., Pi, S., et al. (2019). Real-time machining data application and service based on IMT digital twin. Journal of Intelligent Manufacturing, 31(5), 1113-1132.

[15] Li, C., Wang, Q., Lu, J., et al. (2023). Modeling and identification of abnormal passenger behavior in elevators based on digital twin. Journal of Computer Engineering and Applications, 59(19), 274-284.

[16] Luo, C., Mao, Y., Chen, Z., et al. (2024). Research on fault warning of firing system driven by the fusion of digital twin and neural network. Mechanical Science and Technology, 1-8. https:// doi.org/ 10.13433/j.cnki.1003-8728.20240016.

[17] D.J. Wagg,K. Worden,R.J. Barthorpe,P. Gardner,Digital twins:state-of-the-art and future directions for modeling and simulation in engineering dynamics applications,ASCE-ASME J. Risk Uncertain. Eng. Syst. Part B Mech. Eng. 6 (2020),https://doi.org/10.1115/1.4046739,3.

[18] ISMAIL F B,AL-FAIZ H,HASINI H, et al. A comprehensive review of the dynamic applications of the digital twin technology across diverse energy sectors[J/OL]. Energy Strategy Reviews,2024,52: 101334. DOI:10.1016/j. esr.2024.101334.

[19] EL-GOHARY M,EL-ABED R,OMAR O. Prediction of an Efficient Energy-Consumption Model for Existing Residential Buildings in Lebanon Using an Artificial Neural Network as a Digital Twin in the Era of Climate Change[J/OL]. Buildings,2023,13(12):3074. DOI:10.3390/ buildings13123074.

[20] Lin, F., Xiao, L., Shang, H., et al. (2022). Design and application of digital twinning system for energy internet under the "dual carbon" background. Electric Power Science and Engineering Journal, 37(1), 29-34.

[21] Khajavi, S. H., Motlagh, N. H.,Jaribion, A., et al. (2019). Digital twin:Vision, benefits, boundaries, and creation for buildings. IEEE Access, 7, 147406-147419.

[22] Kor, M., Yitmen, I., & Alizadehsalehi, S. (2022). An investigation for integration of deep learning and digital twins towards Construction 4.0. Smart Sustain, Built Environ.

[23] Lopez, C.E.B. (2021). Real-time event-based platform for the development of digital twin applications. International Journal of Advanced Manufacturing Technology, 116, 835-845.